



Responsebased sea state estimation for onboard DSS Safe and Efficient Marine Operations

Nielsen, Ulrik Dam

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Response-based sea state estimation for onboard DSS - Safe and Efficient *Marine* Operations



Ulrik Dam Nielsen

AMOS Workshop, NTNU, Trondheim,
13th and 14th November, 2014

DTU Mechanical Engineering
Department of Mechanical Engineering

$$(EIv'')'' = q - \rho A \ddot{v} \int_a^b \epsilon \Theta + \sqrt{17} \int \delta e^{i\pi} \{2.718281828\} \chi^2 \sum_i !$$

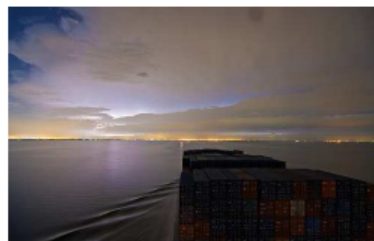
- **Introduction:**
 - **Context**
 - **Monitoring and decision support**
- **Decision support and wave estimation**
- **Wave buoy analogy:**
 - **The concept and modelling approaches**
 - **Results**
- **Results and discussions**
- **Concluding remarks and future work**

The presentation focuses mainly on work made in relation to the wave buoy analogy, where the central point is to use available wave-induced global vessel responses (motion components, accelerations, hull girder strains, etc.) to make on-site sea state estimation from an advancing ship (any floating vessel) in a seaway. Thus, within technical ship operations at sea – and more generally for all maritime operations – knowledge of the onsite sea state can be used to improve both safety and efficiency. In particular, this type of sea state estimation can provide fundamental information to control- and decision support systems (DSS), which also include the area of dynamic positioning, in which the sea state estimate can be used for feed-forward control, improving both station-keeping behaviour and fuel consumption. Moreover, vessel performance systems for onboard as well onshore ('in-house office') fleet analyses gain advantage by having available continuous estimates of the sea state at the particular position.

The presentation focuses mainly on work made in relation to the wave buoy analogy, with responses on-site sea technical sl – knowledge efficiency. Information include the used for fuel consumption onshore ('in continuous



Solution areas



Safe navigation



Fuel saving



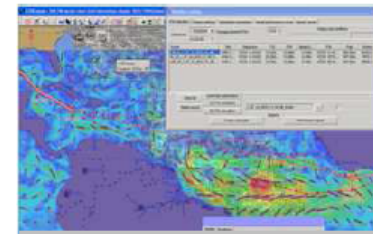
Simulators



Marine Operations



Sloshing avoidance



OEM-solutions

Decision support systems for safe and efficient marine operations:

... guidance with respect to the vessel's speed and/or wave heading in a seaway. Objective is to reduce risk(s) associated to critical response levels and/or improve (fuel) efficiency.

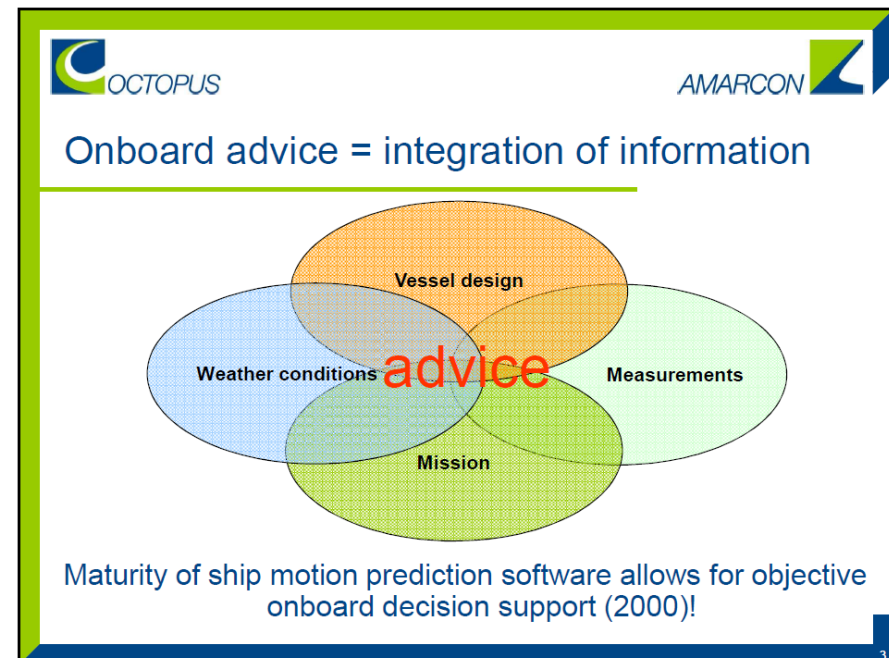
Concern for safety includes, e.g.

- Sea sickness of passengers
- Loss of or damage on containers and cargo
- Structural damage from slamming or wave impacts
- Large roll motions; parametric roll
- Fatigue (accumulation) in the hull girder and other structural details
- ...



Introduction: Monitoring and decision support

- Development of *decision support systems* (DSS) started in the 1970's; due to a general demand for more exact knowledge about behaviour of ships as changes in speed and course were made.
- Increase in vessel size and more optimised ships imply a drift towards the physical limits with respect to capability and survivability.
- In rough weather and at night decisions are sometimes made by pure guess and/or gut feeling only.



Introduction: Monitoring and decision support

The need for guidance...



Typically, decision support systems have two combined and integrated functions;

- **Monitoring:** The current 'state' (weather and wave environment, motions, accelerations, hull girder strains, etc.) of the vessel is recorded by sensor measurements. The state is normally visualised to the ship's master in graphical plots.
- **Guidance:** *Safe and efficient* speed and course options for the next 20 minutes to 3 hours are displayed (graphically); often in terms of polar diagrams. **The given guidance presents 'expected behaviour' and, thus, reliability becomes critical.** Consequently, decision support systems should be risk-based.



From K. Bendix , 05-03-2012 @ Skibsteknisk Selskab

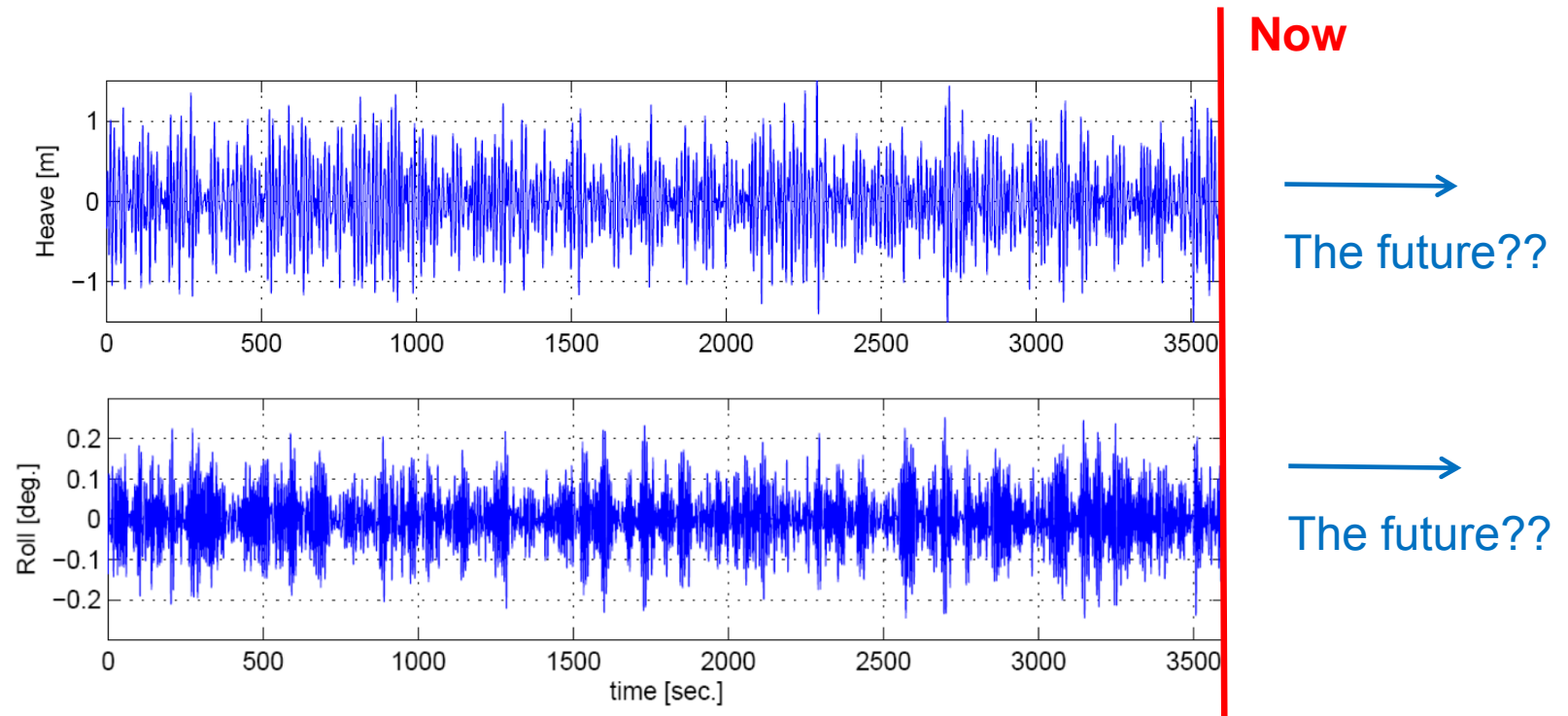
Introduction: Monitoring and decision support

Monitoring



Guidance

Decision support: Statistical response predictions

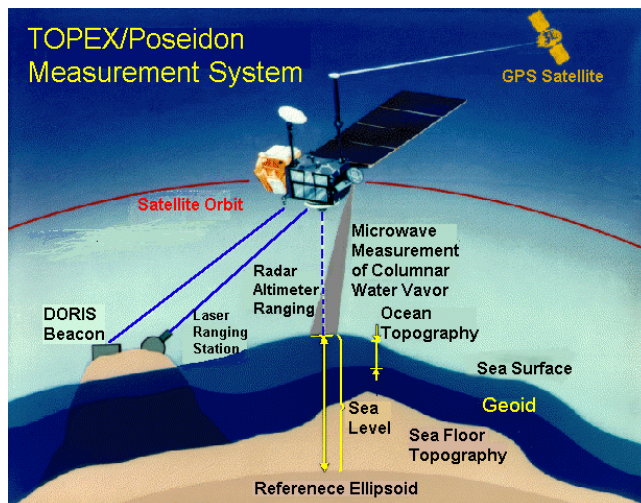


- For stationary conditions and a vessel advancing with constant speed and at a constant wave heading, statistical predictions of future responses can - to some extent - be derived on the basis of trend analysis of the past recorded signals.
- **However, to include the effect of changing operational parameters (speed and heading), information about the on-site sea state is required for any type of response analysis; the responses being linear or non-linear.**

Decision support: Means for wave estimation

- Well-known “typical” means to estimate sea states or, equivalently, wave energy spectra: Wave rider buoys, satellite measurements, and wave radars.

- Classical **wave rider buoys**; any wave action makes the buoy moving. 6-dof (3 translations and 3 rotations) “problem”
- Measurements of 3 accelerations and 3 angular rates are processed and, from an inverse problem, the “wave action” is solved.
- Due to their fixed position, the information from wave buoys is difficult to use (in particular on open ocean where the information is scarce).



- **Satellite measurements** offer a paramount tool for the statistical description and treatment of ocean waves and sea states. However, presently satellite measurements cannot be used in the context of DSS. (Further developments are needed.)

Decision support: Means for wave estimation

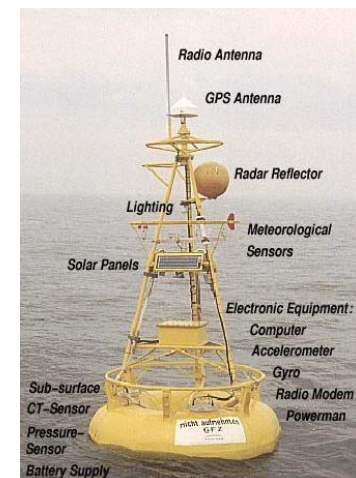
- **Wave radar systems** work on a continuous basis and at the exact position of the vessel. Several studies report good and reliable estimation of sea states, but reports on the opposite also exist. Systems are somewhat expensive and require careful calibration.



- For decision support systems the sea state parameters are needed on a continuous basis (i.e. on a 10-20 minutes basis) and at the exact position of the moving vessel.

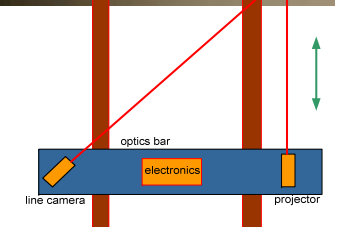
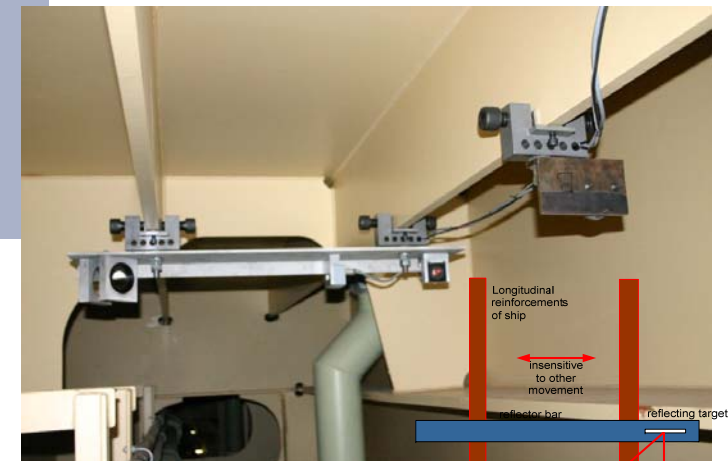
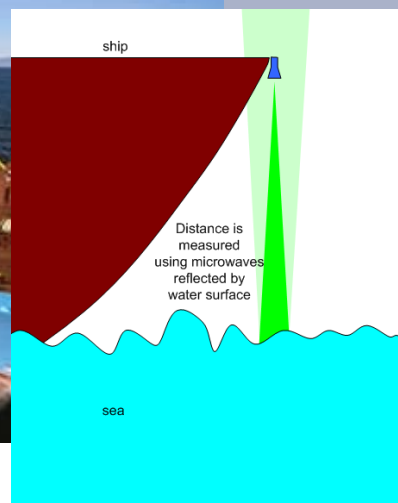
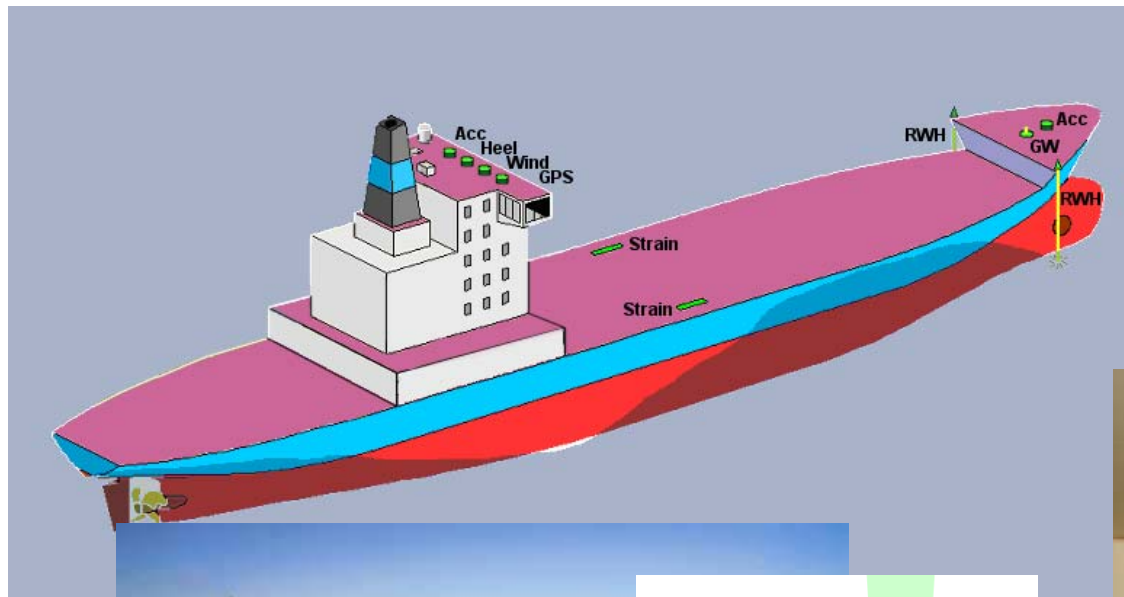


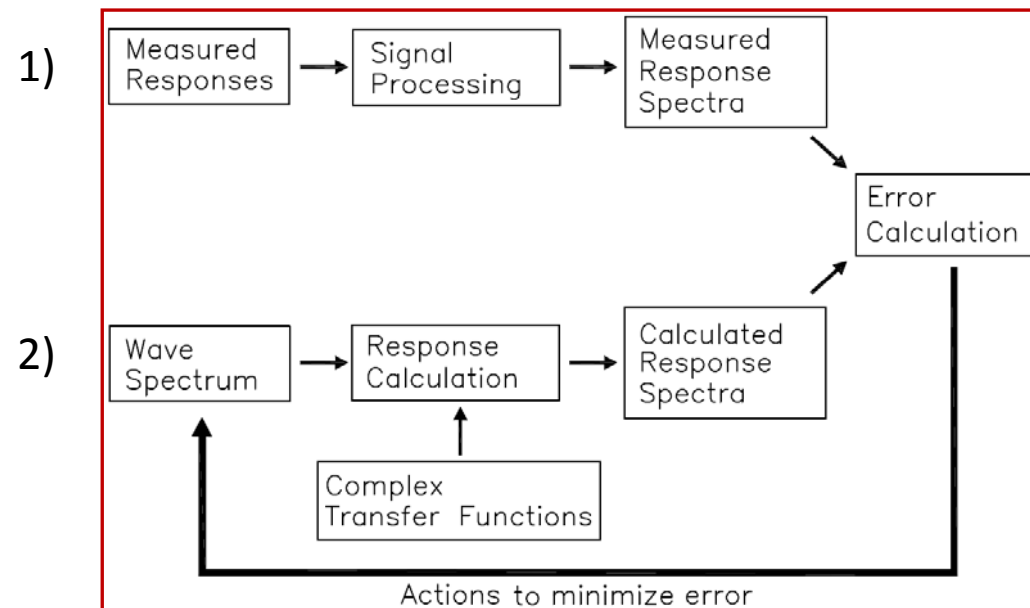
A wave rider buoy is a **floating structure**; and so is any type of ship...
'The wave buoy analogy'



Wave buoy analogy

Estimation of wave spectra based on measured ship responses
(measurements by a number of sensors)



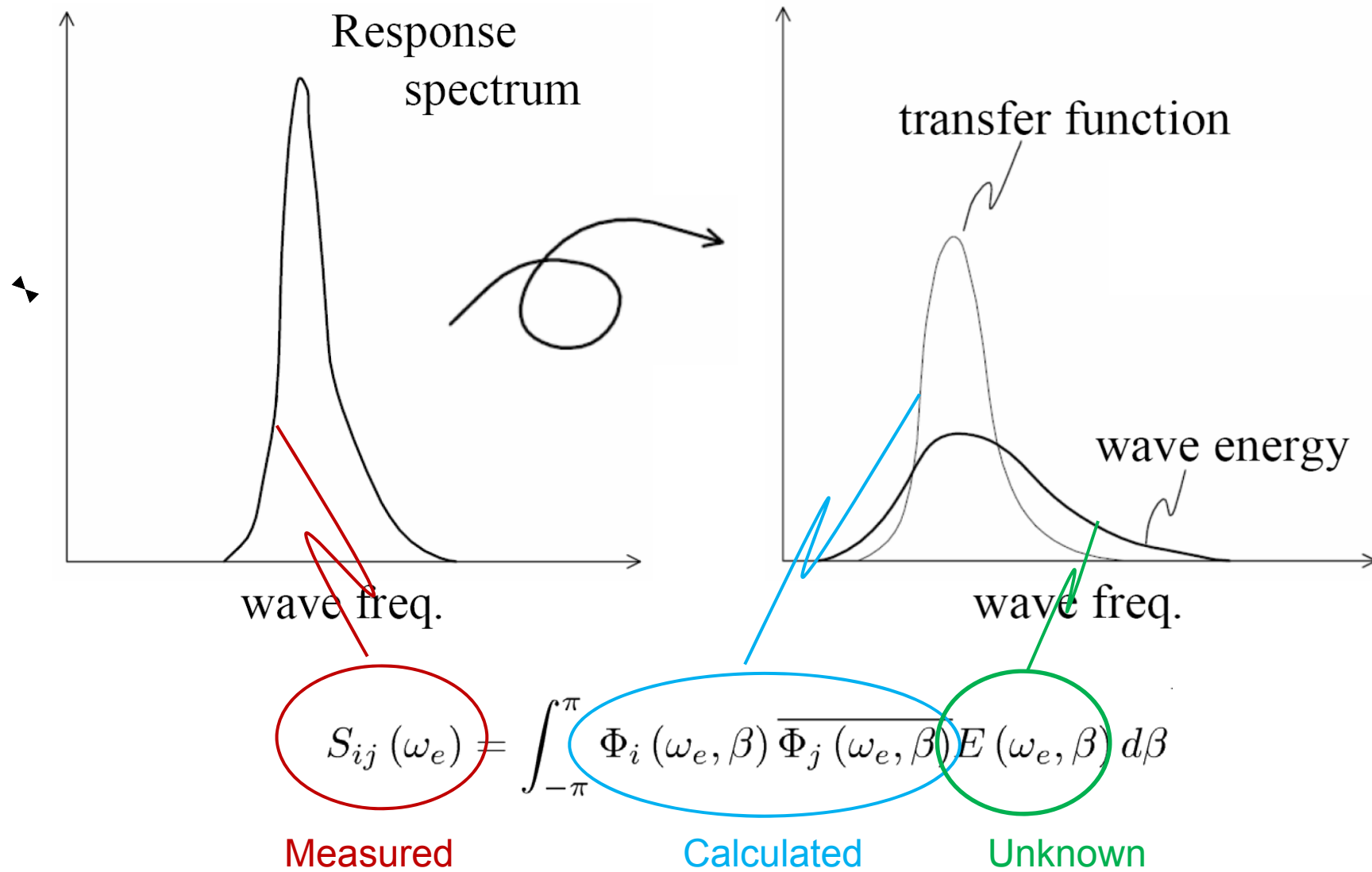


1) Measurements: from measured ship responses, response spectra are derived.

2) Calculations: by combination of a wave spectrum and linear transfer functions of the responses, response spectra are *calculated*.

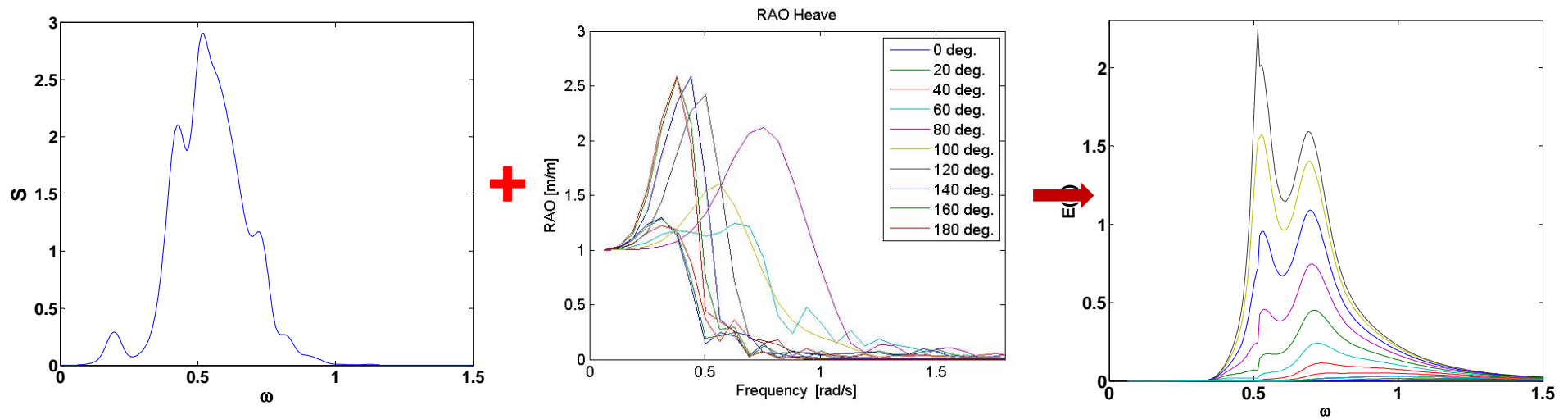
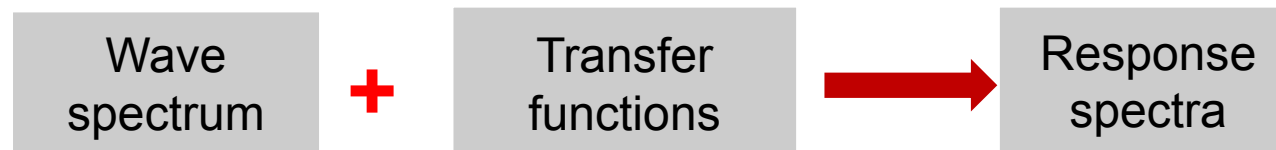
- **Assumption**: Linear relationship between wave excitations and ship responses (linear transfer functions).
- Representations by parametric and non-parametric modelling. Studies by e.g. Iseki and Terada (2002), Tannuri et al. (2003), Aschehoug (2003), Pascoal et al. (2007) and Nielsen (2006, 2008).
- **Note**: Estimations are, theoretically, likely to be less reliable during severe sea states (non-linearity between excitations and responses...).

Wave buoy analogy



Wave buoy analogy: An illustration

Typical scenario:



Wave buoy analogy: An illustration

The “inverse” process - i.e. the wave buoy analogy:

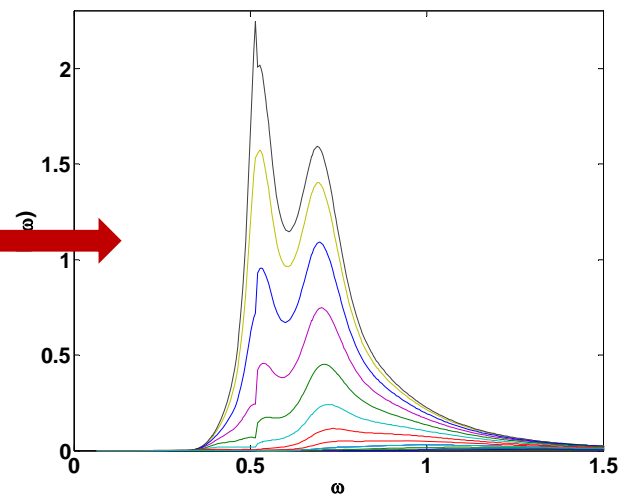
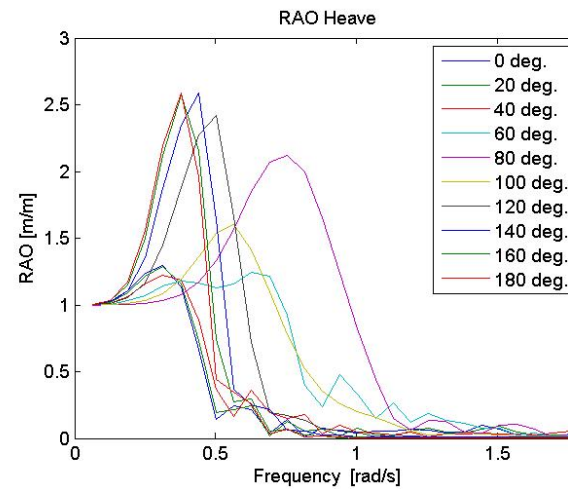
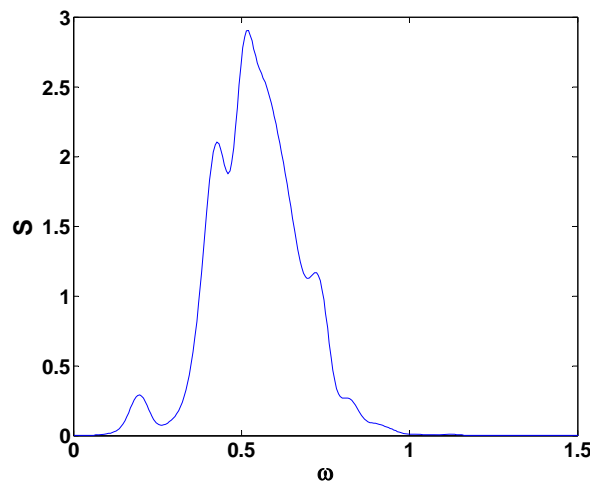
Wave
spectrum



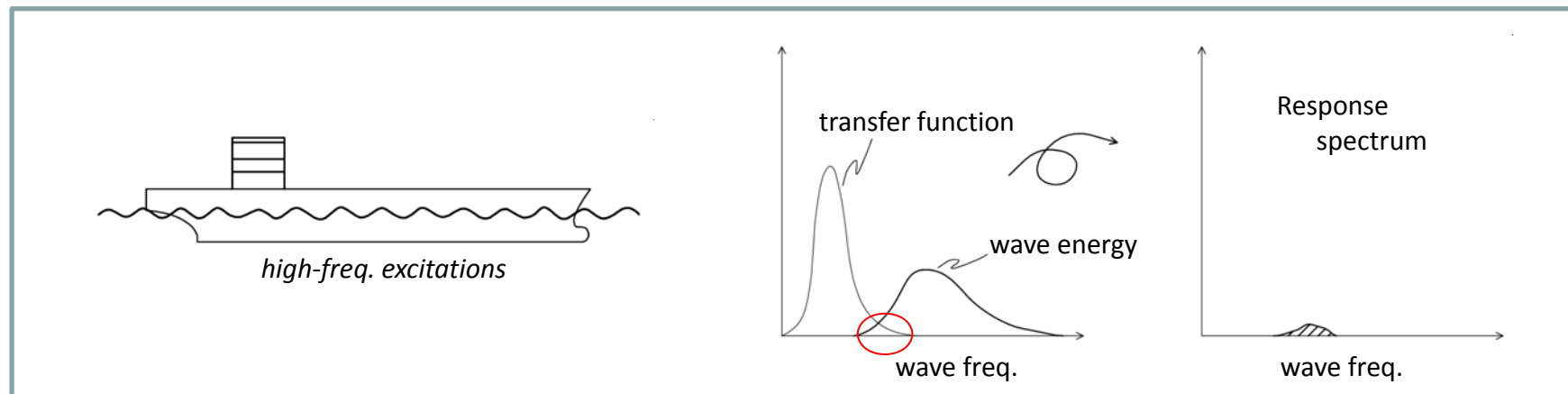
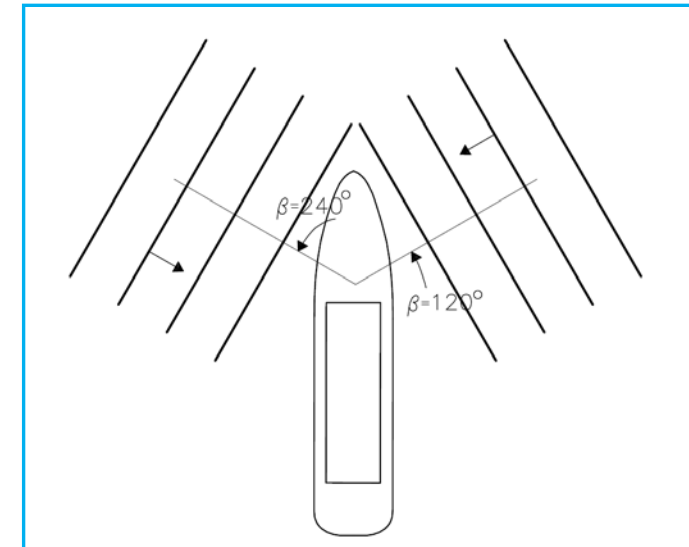
Transfer
functions



Response
spectra

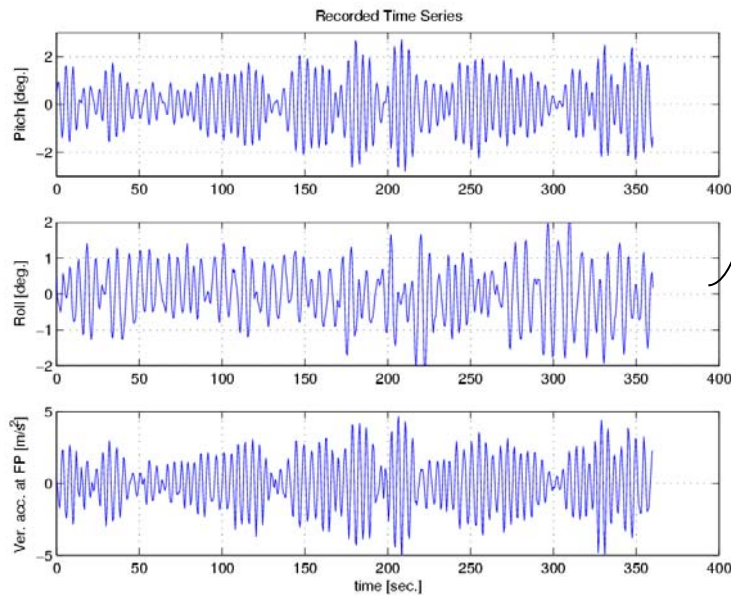


- **Global ship responses**, including the complex-valued transfer functions (acceleration(s), roll, wave induced VBM amidships, ...)
- A **set of three responses** is simultaneously considered. This has shown to be the best compromise.
- At least one **response must exhibit port/starboard side asymmetry** in its corresponding transfer function (e.g. sway and roll).
- Frequency insensitivity – the **ship needs to respond to the waves**; consider responses with different frequency sensitivity.

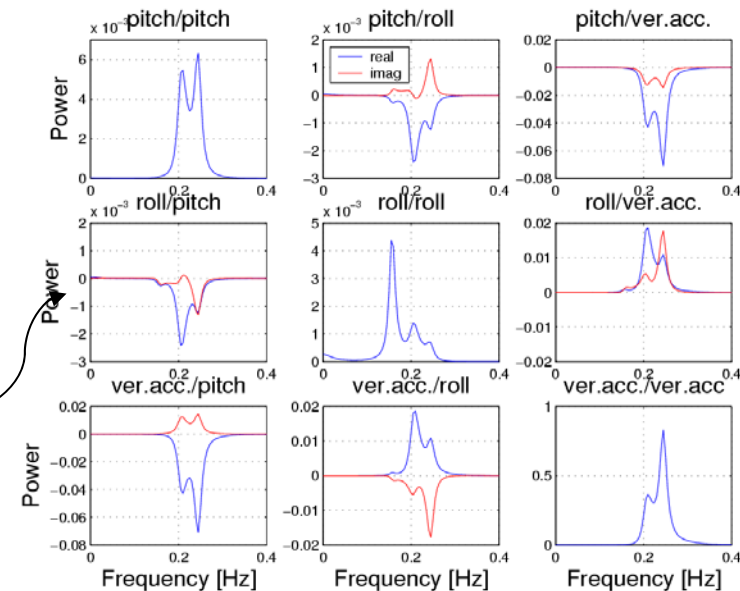


Wave buoy analogy: Governing equation(s)

- Measurement of, say, three ship responses:



Cross
Spectral
Analysis

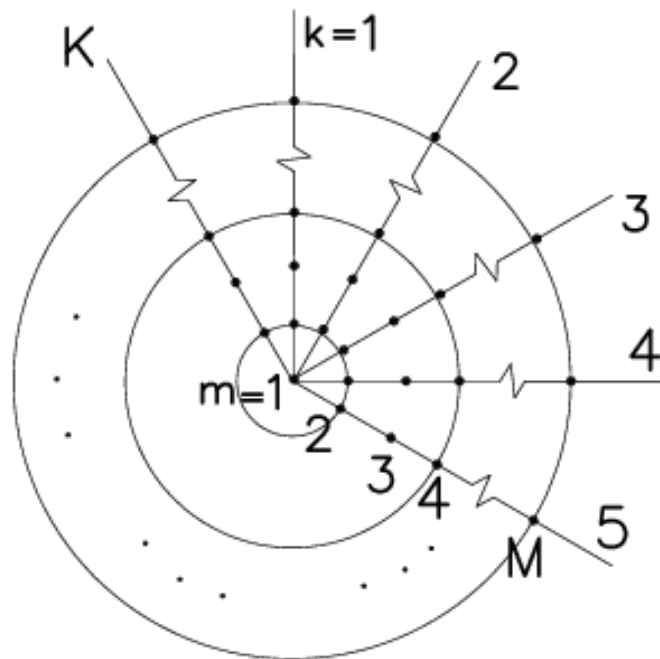


- 9 response spectra are obtained, coupled spectra have complex values

- Spectral analysis:

$$S_{ij}(\omega_e) = \int_{-\pi}^{\pi} \Phi_i(\omega_e, \beta) \overline{\Phi_j(\omega_e, \beta)} E(\omega_e, \beta) d\beta \quad \text{or} \quad \mathbf{b} = \mathbf{A}\mathbf{f}(\mathbf{x}) \quad , \quad \mathbf{f}(\mathbf{x}) = E(\omega, \beta)$$

$$S_{ij}(\omega_e) = \int_{-\pi}^{\pi} \Phi_i(\omega_e, \beta) \overline{\Phi_j(\omega_e, \beta)} E(\omega_e, \beta) d\beta \quad (1)$$



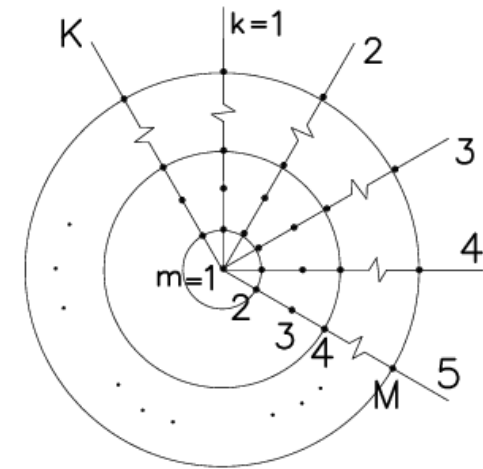
- Equations are set up for at set of encounter frequencies, $\omega_e = \Delta\omega_e \cdot l$, $l = 1, 2, \dots, L$
- Relationship between encounter and wave frequencies is secured by discretising the wave field into a number (M) of wave frequencies and number (K) of directions.
- That is, the wave spectrum, $E(\omega, \beta)$, is determined in $K \cdot M$ points,
- and the solution is sought from L equations.
- Solution obtained by minimising the difference between the left- and the right-hand side of (1):

$$\|\mathbf{A}\mathbf{f}(\mathbf{x}) - \mathbf{b}\|^2$$

Two procedures:

1) Non-parametric (Bayesian) modelling

- In general, more unknowns than equations.
- Assumptions: 1) Introduction of the error as white noise (stochastic viewpoint); 2) Non-negativity constraint; 3) Introduction of prior information (\sim 'Bayesian approach').



$$\mathbf{f}(\mathbf{x}) = E(\omega, \beta)$$

2) Parametric modelling

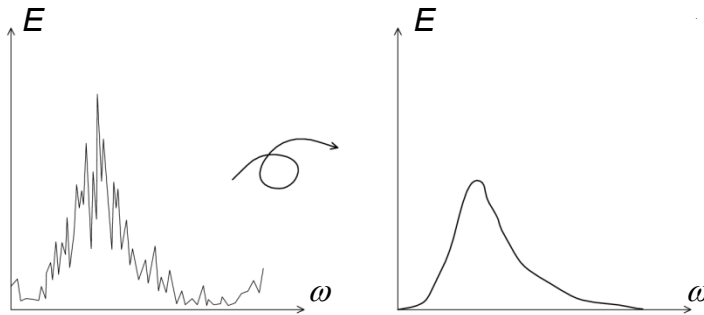
- Introduction of parameterised wave spectrum:

$$E(\omega, \theta) = \frac{1}{4} \sum_{i=1}^3 \frac{\left(\frac{4\lambda_i + 1}{4} \omega_{p,i}^4 \right)^{\lambda_i}}{\Gamma(\lambda_i)} \frac{H_{s,i}^2}{\omega^{4\lambda_i + 1}} A(s_i) \cos^{2s_i} \left(\frac{\theta - \theta_{mean,i}}{2} \right) \exp \left[-\frac{4\lambda_i + 1}{4} \left(\frac{\omega_{p,i}}{\omega} \right)^4 \right]$$

- I.e., the solution is a set of optimised wave parameters.

Prior information

- Additional equations established by use of **prior information**, accordingly
 - a) the wave energy spectrum is expected to be smooth, and
 - b) the energy of ocean waves is expected to vanish for (very) low/high frequencies.



- Mathematically, seek to
 - a) minimise the curvature of $E(\omega, \beta)$, i.e. smoothing for **both** ω and β
 - b) minimise $E(\omega, \beta)$ for low/high ω

- How much smoothing is needed??
- It is a compromise between agreement of the left- and right-hand sides of the governing equation system and smoothness of the spectrum.

- The amount of smoothing is controlled by so-called *hyperparameters*, u and v , so that solution is obtained by minimising

$$S(\mathbf{x}) = \|\mathbf{A}\mathbf{f}(\mathbf{x}) - \mathbf{b}\|^2 + \mathbf{x}^T (u^2 \mathbf{H}_1 + v^2 \mathbf{H}_2) \mathbf{x}$$

- The optimal values of u and v must be determined by *some* criterion, ABIC.

The wave spectrum is modelled as a 15 (3 x 5) parameter standard spectrum (Hogben and Cobb, 1985):

$$E(\omega, \theta) = \frac{1}{4} \sum_{i=1}^3 \frac{\left(\frac{4\lambda_i + 1}{4} \omega_{p,i}^4 \right)^{\lambda_i}}{\Gamma(\lambda_i)} \frac{H_{s,i}^2}{\omega^{4\lambda_i + 1}} A(s_i) \cos^{2s_i} \left(\frac{\theta - \theta_{mean,i}}{2} \right) \exp \left[-\frac{4\lambda_i + 1}{4} \left(\frac{\omega_{p,i}}{\omega} \right)^4 \right]$$

- Mixed sea is allowed
- Non-linear optimisation problem established by minimising the difference between left- and right-hand side from
- The solution is a set of *optimised* parameters

Overview

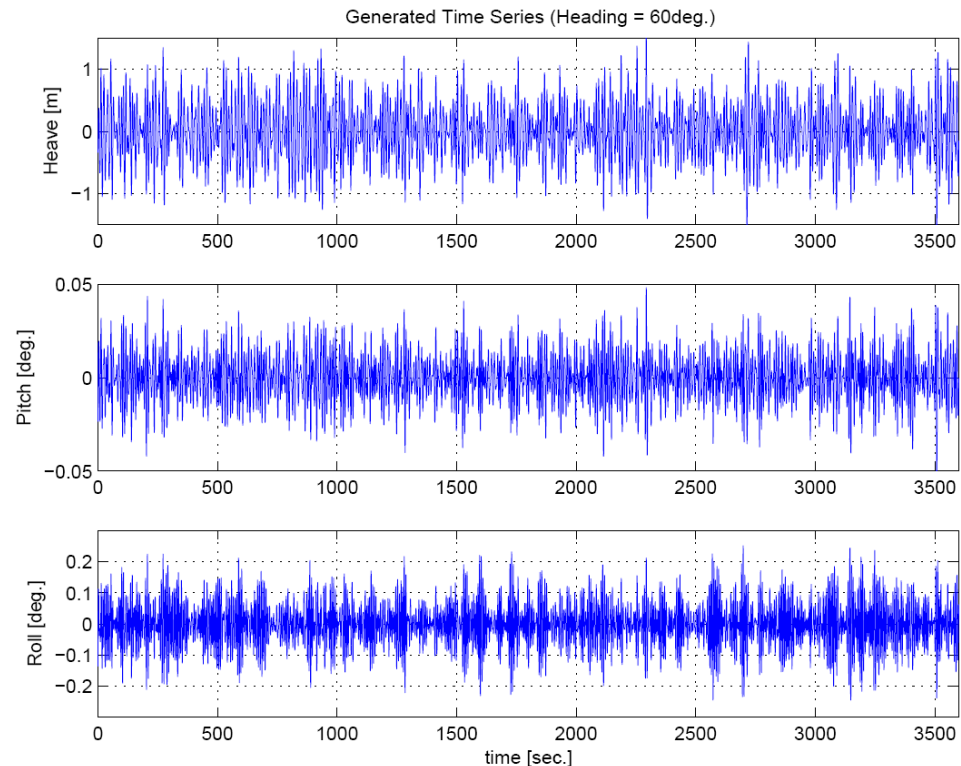
- 1) A study based on only **numerical simulations**
 - LNG carrier
 - responses: {heave, pitch, roll}(Nielsen, 2008a, 2010)
- 2) Analysis of **full-scale motion measurements**
 - container ship
 - eight data sets, A, B, ..., H. Duration of 15 minutes.
 - responses: {heave, pitch, roll}
 - measurements recorded during operation.
 - comparison with wave radar (WAVEX)(Nielsen, 2006, 2008b)
- 3) Analysis of **full-scale motion measurements from sea trial**
 - research vessel (DRDC Atlantic)
 - comparisons with buoy data(Nielsen, 2011, 2012)

Numerical simulations

(generation of time histories data)

▪ Time series data where the underlying wave parameters are precisely known.

▪ LNG carrier. RAOs calculated by 3D panel code (Wasim)



$$R(t) = \sum_{n=1}^N \sum_{m=1}^M [u_{mn} c_{mn}(t) + \bar{u}_{mn} \bar{c}_{mn}(t)]$$

$$c_{mn}(t) = \sigma_{mn} |\Phi_R(\omega_n, \beta_m)| \cos(\omega_{e,n} t + \epsilon_{mn})$$

$$\bar{c}_{mn}(t) = -\sigma_{mn} |\Phi_R(\omega_n, \beta_m)| \sin(\omega_{e,n} t + \epsilon_{mn})$$

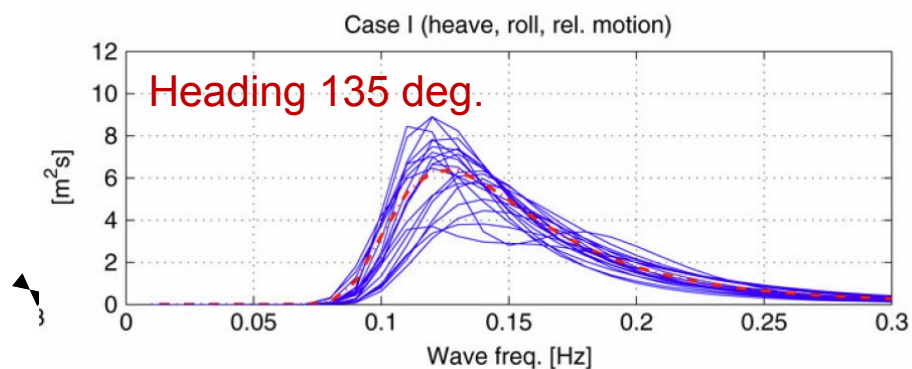
$$\sigma_{mn}^2 = E(\omega_n, \beta_m) \Delta \omega_n \Delta \beta_m$$

$$\omega_e = \omega - \omega^2 A, \quad A = \frac{V}{g} \cos \beta$$

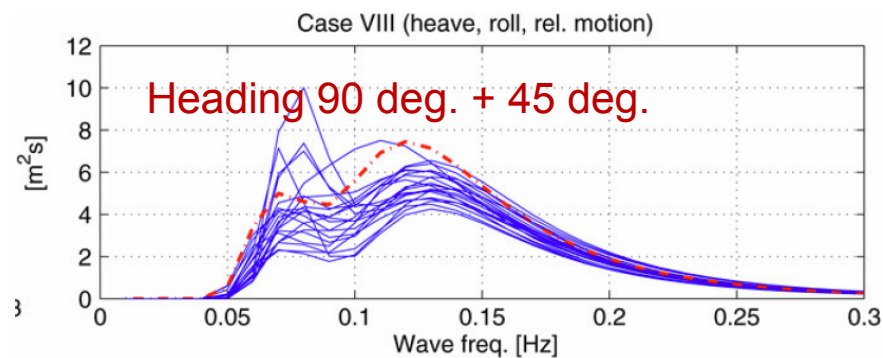
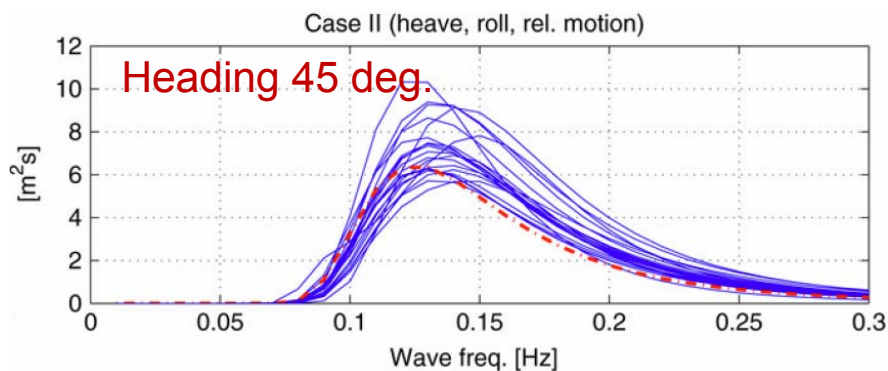
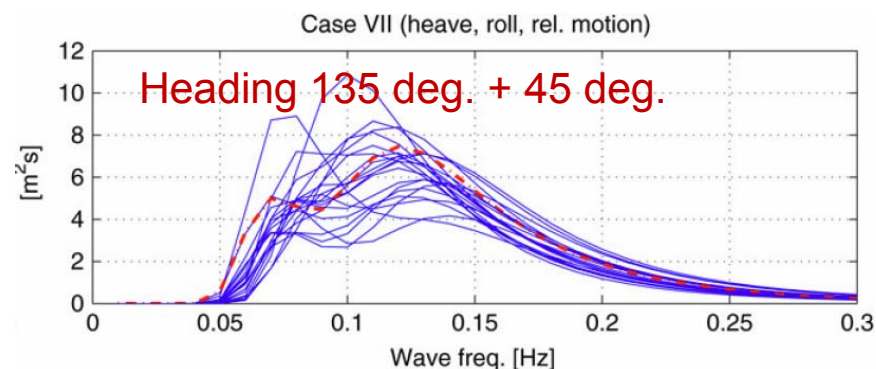
Numerical simulations

(generation of time histories data)

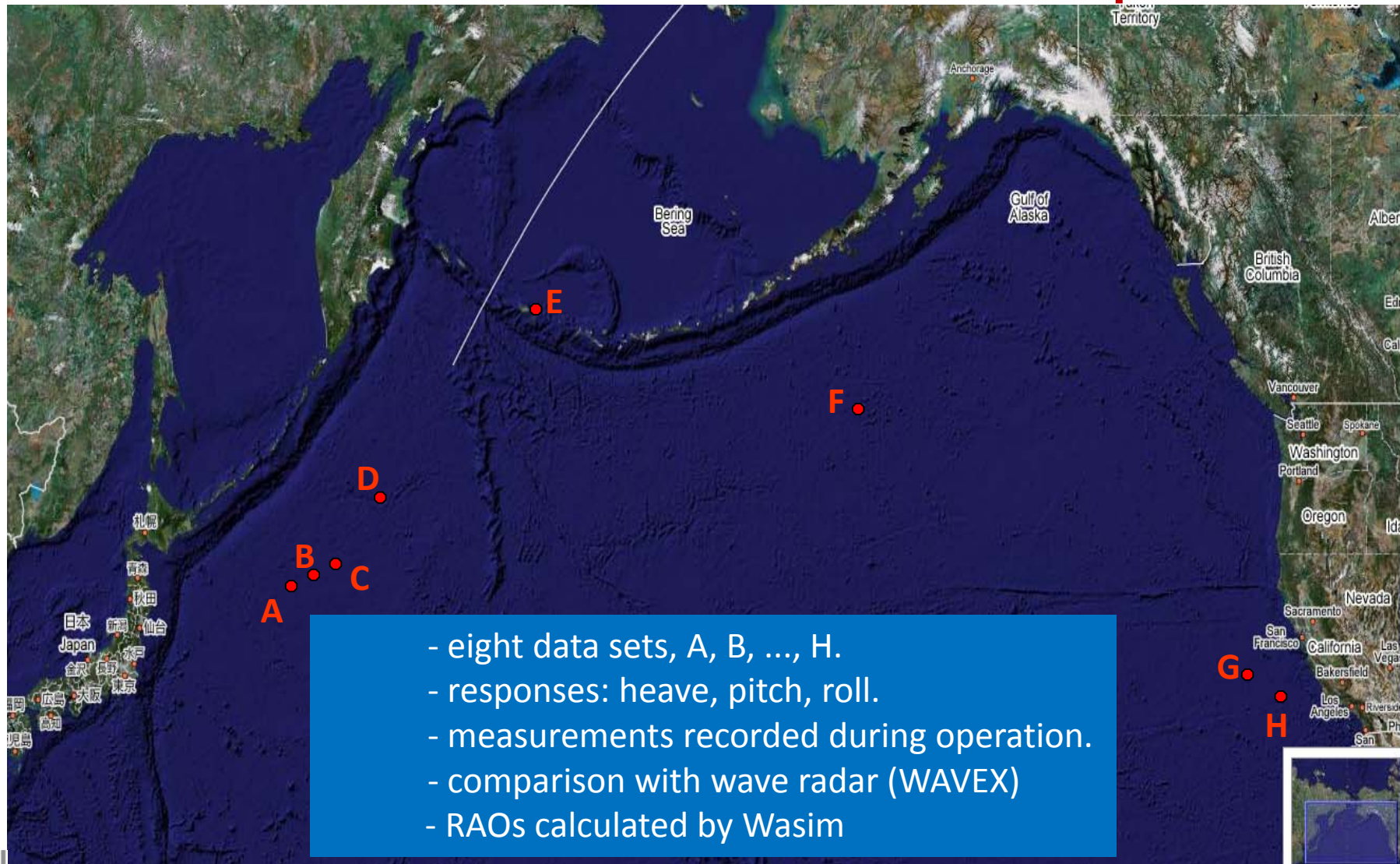
Uni-modal sea states



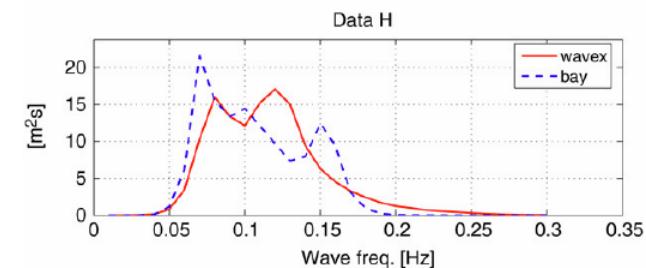
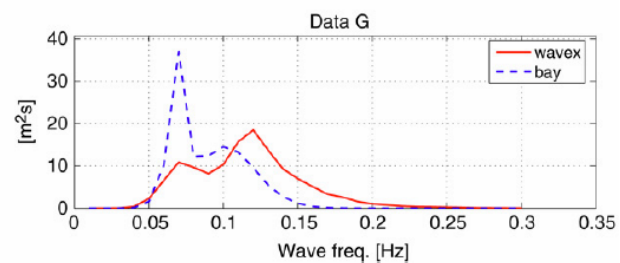
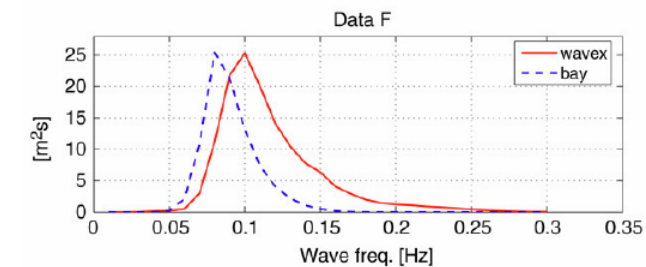
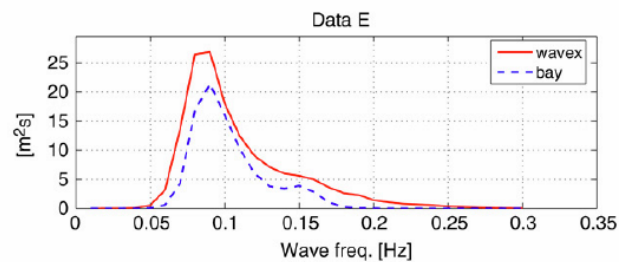
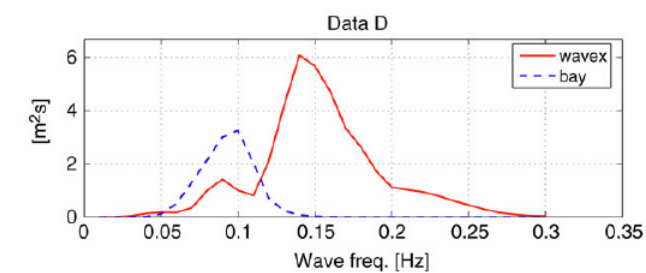
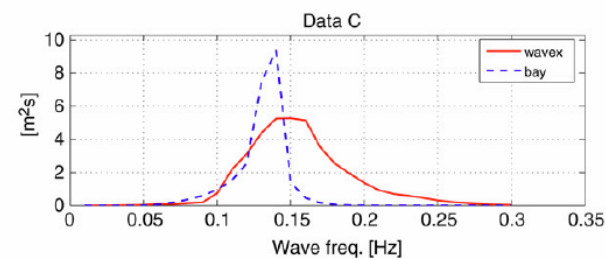
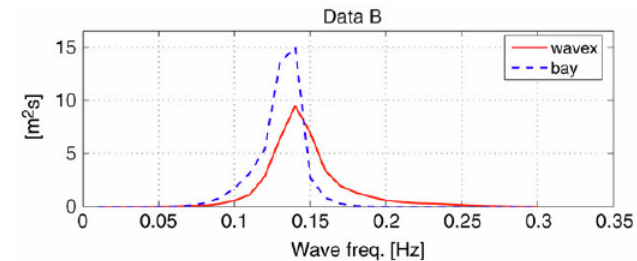
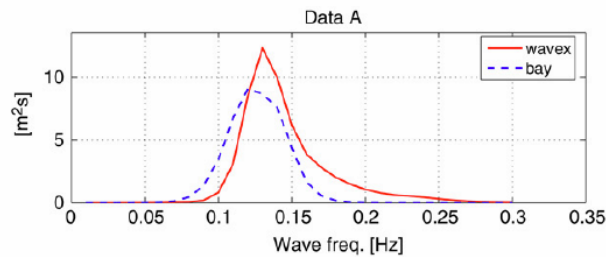
Mixed sea (wind + swell)



Full-scale measurements from a container ship



Full-scale measurements from a container ship



Full-scale measurements from sea trials (DRDC)



Fig. 2: The Canadian Navy research ship CFAV Quest.
($L = 71.6$ m, $B = 12.8$ m, $T = 4.8$ m, $C_b = 0.51$)

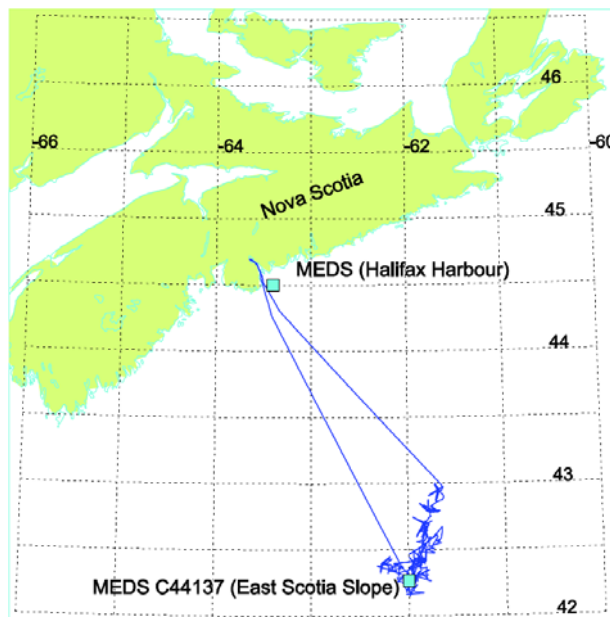


Fig. 3: Voyage map of sea trials.

- Responses: roll rate, roll angle, pitch rate, pitch angle, horizontal acc. and vertical acc. (all recorded at bridge).
- Ship motions calculated by DRDC (SHIPMO7) using 2D strip theory
- Sea state monitored continuously by three wave rider buoys (MEDS C44137 and two drifting Triaxys buoys)
- 16 sets of trials, all with identical “relative” run patterns

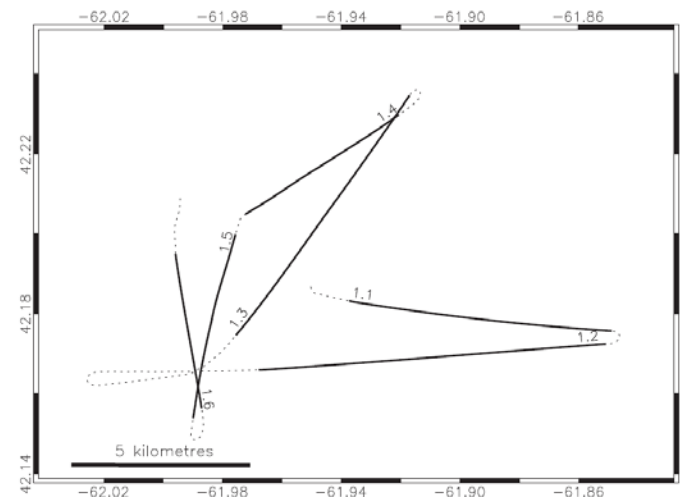
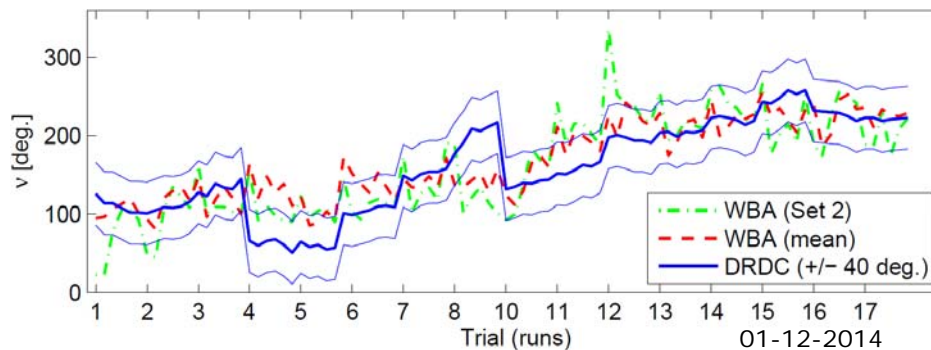
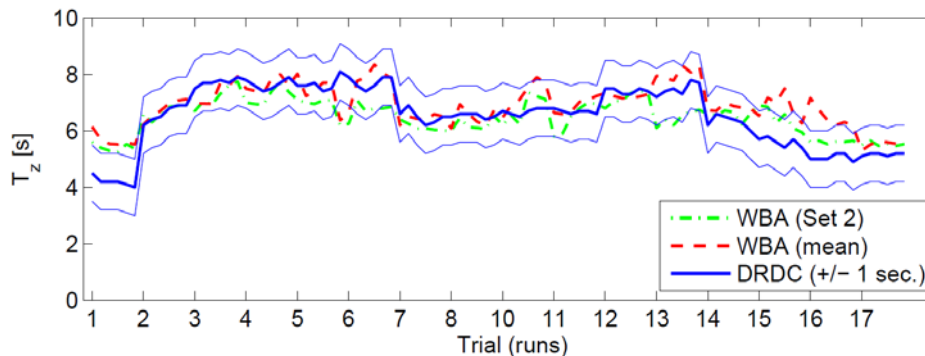
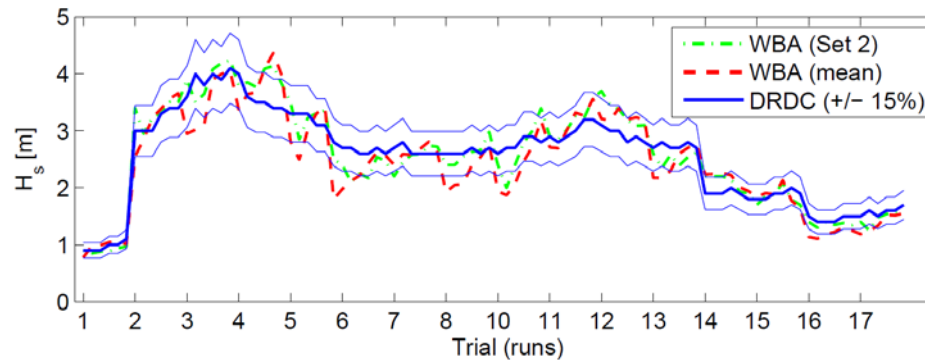


Fig. 4: Run pattern of trial no. 1.

Full-scale measurements from sea trials (DRDC)



WBA: Results by wave buoy analogy.

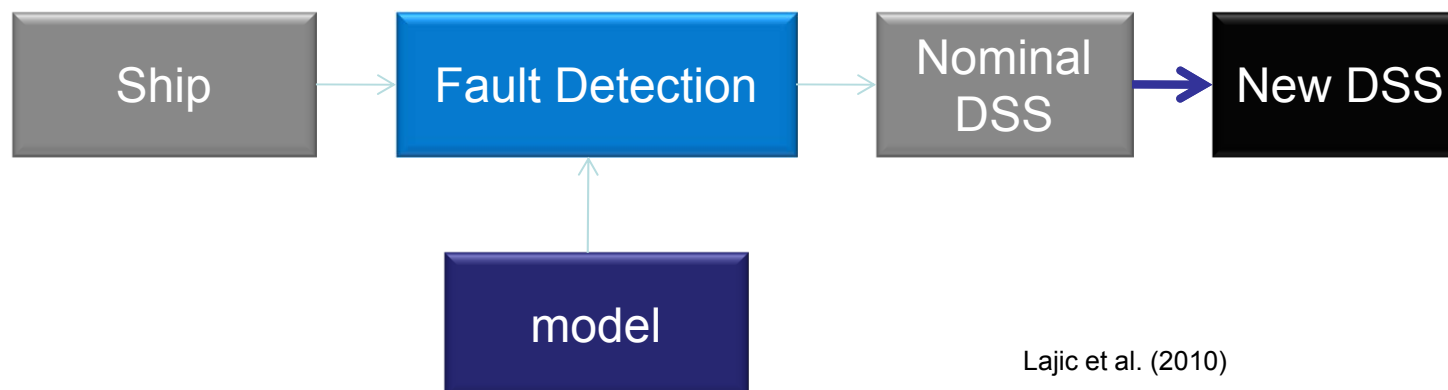
DRDC: Results obtained as the weighted average value of three floating wave rider buoys.



- Several means and methods (e.g. wave ride buoys, satellite meas., wave radars) exist to estimate wave parameters.
- In DSS, wave parameters are needed continuously and at actual position of the vessel. (Exclusion of some means...)
- By use of the wave buoy analogy the ship is itself considered as a wave buoy and, hence, wave estimations can be based on measured ship responses.
- Comparisons based on numerical simulations show good agreement.
- Comparisons based on full-scale data show reasonable agreement with estimates from wave radar and wave rider buoy measurements.
- The phenomenon of filtering will affect the wave estimations.
- Which combination of responses is – under given conditions – the best? And, can this combination be chosen automatically? What about uncertainties in RAOs and sea state estimation?
Ongoing work as a Ph.D. project (Ms Najmeh Montazeri).

How to – automatically – select the best set of responses under given operational conditions and how to incorporate uncertainties?!

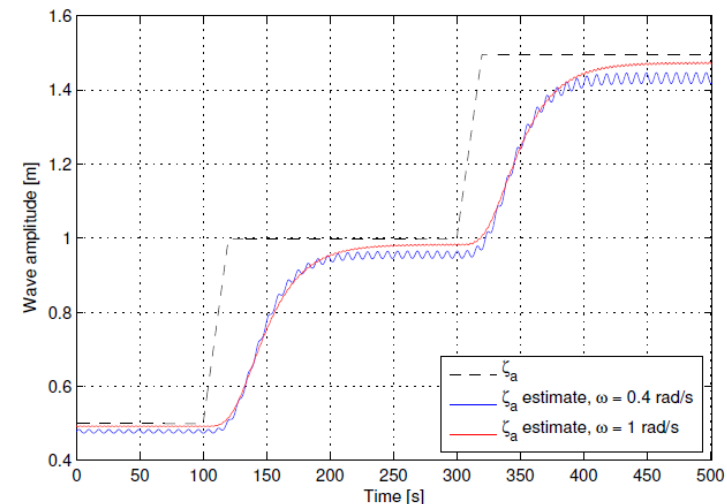
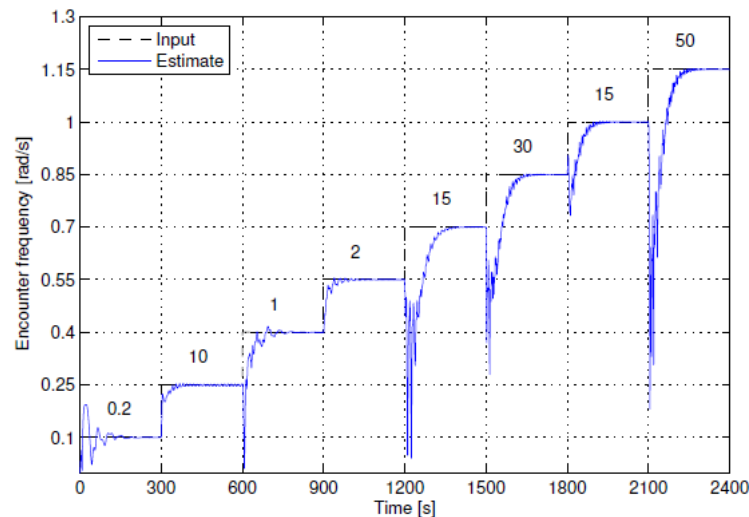
- Depending on operational conditions, certain responses may be better than others to include in the combination of (three) considered responses.
- Uncertainties are related to both measurements and transfer functions. Uncertainty modelling should be considered to increase reliability.
- What about fault-detection and fault-tolerant approaches...



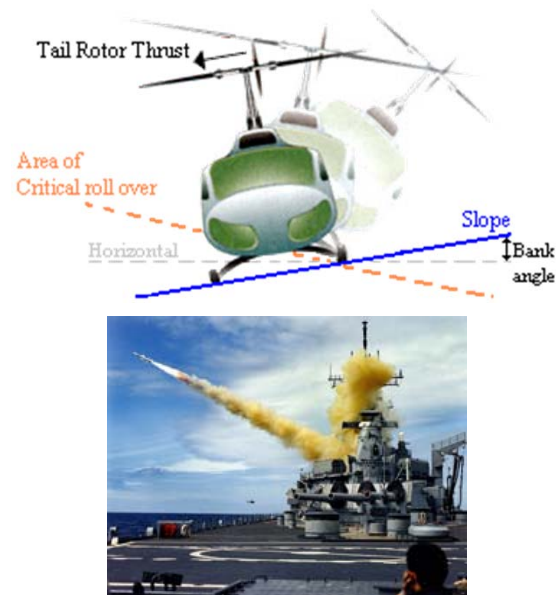
Lajic et al. (2010)

Future work: A “time domain” approach...

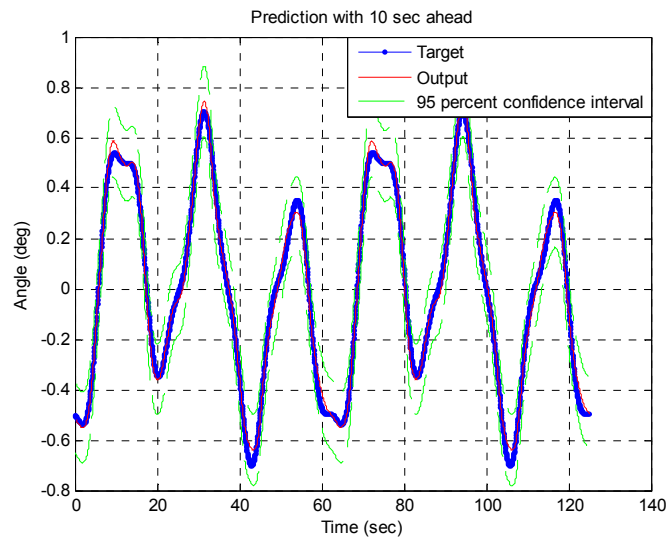
- Initiated in an MSc-study (Bjerregård, 2014)
 - Combines signal- and model-based approaches (Aronovskii filter, Extended Kalman filter, Recursive least-squares filter), where overall methodology relies on ideas developed within areas of *control theory* and *automation*
 - Advantageous in non-stationary conditions (which in principle exist at all times...) and updates of sea state are available in truly continuous sense
- Case-study of a semi-sub (zero-forward speed and regular wave(s))



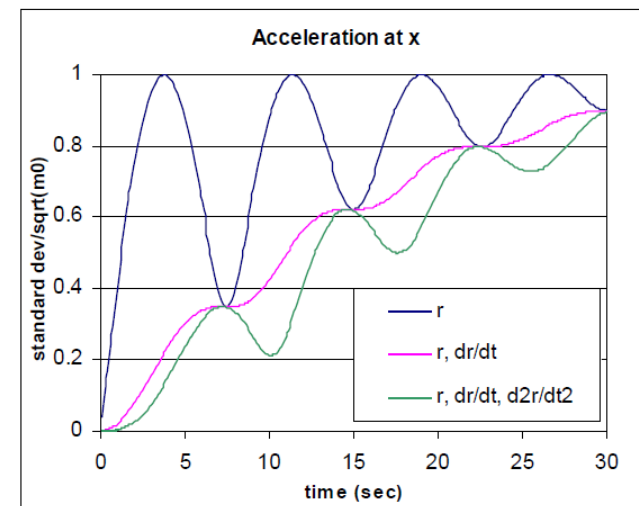
Future work: “Deterministic” response predictions (5 – 30 sec.)



- Ship-to-ship interactions
- Helicopter landings
- Crane operations
- ...
- Newly started research topic....



Khan et al. (2006)



Jensen et al. (2013)

The end



Thank you